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NACA Research on High-Energy Propellants

The National Advisory Committee for Aeronautics (NACA), established in 1915 to develop practical solutions for the problems of flight, showed interest in liquid hydrogen as a fuel in 1939 but did nothing about it for over a decade. The early interest came as a surprise to Robert Goddard when he visited NACA's director, George W. Lewis, in March 1939. He learned that "the NACA is considering liquid H [hydrogen] as a fuel (!) possibly used with air for rocket propulsion."[1] Four days after his visit, still amazed, Goddard wrote to a friend:

> On talking with Dr. Lewis of the NACA I found that they are contemplating using liquid hydrogen, because of its low weight and high heat value, as a fuel with atmospheric air. I mention this because liquid hydrogen is expensive and difficult to transport and store . . . and also because tanks of it have to be surrounded by liquid oxygen or liquid nitrogen. It makes my use and advocation of liquid oxygen seem really conservative by comparison. The main point is that even with the extreme difficulty of liquid hydrogen, its use is being considered by a body as serious as the NACA.[2]

What did Lewis have in mind? The use of atmospheric air rather than readily available liquid oxygen suggests that he may not have been thinking of a simple rocket for propulsion but a rocket as a component in an air-breathing engine, possibly applied to a turbine engine. He may have heard about the early work of Hans von Ohain, employed in April 1936 by Ernst Heinkel to develop a turbojet engine. Pressed for time, von Ohain turned to gaseous hydrogen as a fuel for convenience in tests beginning in early 1937 and found that his turbojet engine worked well using hydrogen.*

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*Von Ohain's work made hydrogen one of the first fuels to be used in turbojet engines. Lewis visited Germany in September–October 1936, returning on the hydrogen-filled *Hindenburg* which impressed him so much he wrote a report on it. Lewis may have learned about von Ohain's work during his visit or through later reports of John J. Ide, NACA representative stationed in Paris, or through intelligence reports which he received about aeronautical developments. Hans von Ohain to author, 21 May 1974; George W. Lewis file, NASA History Office; telephone interview with Robert E. Littell, former NACA aide at headquarters, 20 Aug. 1973.

On the other hand, Lewis had long been thinking about rocket research, for 18 months earlier he had asked NACA member Charles A. Lindbergh, then in England, "for recommendations with reference to any rocket research for the National Advisory Committee for Aeronautics to carry on."[3] Lindbergh, in turn, sought the advice of Robert Goddard who suggested "several lines of research: for example, liquid propulsion rockets for gliders; application of rockets to turbines; rockets for accelerating and decelerating planes; development of combustion chambers of large thrust."[4] In 1938 Lewis wrote to Goddard expressing interest in his high-speed work and Goddard asked for NACA wind-tunnel tests to determine the flight stability of his rockets. Was Lewis thinking of Goddard's suggestion of applying rockets to turbines, a concept appearing later as a "turborocket"? Whatever Lewis had in mind remains a mystery for, characteristically, he kept his planning informal and shared it with few others. The incident, however, illustrates the dual nature of NACA during that period—receptive to new ideas but conservative and slow in entering new fields of research. It also indicates the ease with which liquid hydrogen comes to mind when engineers think of high-energy fuels.

In 1944, seven years after asking Lindbergh about recommendations for rocket research and apparently after some prodding by Wright Field, Lewis authorized the construction of four simple rocket test cells at the Aircraft Engine Research Laboratory in Cleveland.[5]

The information on German jet propulsion and rocket developments, which increased from a trickle in 1943–1944 to a flood of captured documents in 1945, made NACA officials realize how far behind they had fallen in these new propulsion systems. In the fall of 1945, a sweeping reorganization of the Cleveland engine laboratory caught all but senior officials by surprise. Overnight, research emphasis shifted from piston engines to jet engines (turbojet and ramjet) with some work on rockets. The rocket research was kept small because of the conservative nature of NACA and the influence of its chairman, Jerome C. Hunsaker, who shared with many the belief that rockets were more applicable to artillery than aircraft and had no place in an aeronautical research laboratory. The word "rocket" was avoided in the organizational name in favor of "high-pressure combustion."

The rocket group at the Cleveland laboratory concentrated on high-energy, liquid-propellant rocket engines with teams working on propellant performance (theoretical and experimental), combustion, and cooling.* The propellant work followed the logical path of computing the theoretical performance of several fuel-oxidizer combinations over a range of operating conditions and selecting the most promising for experimental investigation. By 1948, Riley Miller and Paul Ordin reported calculations of a number of propellant combinations containing hydrogen, nitrogen, and oxygen atoms, with liquid hydrogen giving the highest exhaust velocity and having the lowest propellant density.[6] The same year, Vearl Huff and his associates made a major contribution to theoretical performance techniques by developing a convergent, successive approximation method that saved considerable time over other methods.[7]

*The rocket section was part of a combustion branch headed by Walter T. Olson in a division headed by Benjamin Pinkel. Joseph R. Dietrich was the first head of the rocket section, followed by Everett R. Bernardo, and the author in 1948.

High-energy rocket propellants were difficult to obtain, for most were available only in small quantities. The NACA researchers passed by liquid hydrogen in favor of hydrazine and diborane as fuels and 100 percent hydrogen peroxide, chlorine trifluoride, liquid oxygen, and liquid fluorine as oxidizers.[8]

Calculated risks were taken to transport comparatively rare samples to the laboratory. Louis Gibbons, chief of fuels research, brought a gallon of pure hydrogen peroxide from Buffalo clamped between his knees in an all-night train ride. Paul Ordin used much the same method in bringing a sample of hydrazine from St. Louis. The first diborane, nested in dry ice, was delivered by private automobile from Buffalo. The first liquid fluorine was obtained from downtown Cleveland and transported in a special laboratory-built trailer escorted by police.[9]

During the 1947–1949 period, diborane was of great interest as a rocket fuel, but experiments soon revealed that it had great disadvantages and its theoretical promise could not be realized. When used with liquid oxygen or hydrogen peroxide, diborane formed boron oxides which deposited in the rocket nozzle and degraded performance.[10] When used with liquid fluorine, the combustion products were volatile, but the absence of deposits was replaced with a greater problem—difficulty in cooling. The theoretical flame temperature of diborane-fluorine under rocket operating conditions is about 5400 K, far higher than many other propellants. Moreover, neither diborane nor fluorine is suitable as a regenerative coolant, which means a third fluid is required for cooling, seriously degrading performance. Although experimental performance of diborane-fluorine was measured, it became apparent by the early 1950s that diborane was not a good rocket fuel.[11] The experience with diborane showed not only the limitations of theoretical considerations in selecting propellants but also the value of experiments in revealing practical problems.

In 1949, the acceleration in aeronautical research brought another major reorganization to the Lewis Flight Propulsion Laboratory.* Its director remained Edward R. Sharp, a gregarious and able administrator who had started as an apprentice at the Langley laboratory. Technical management was strengthened by elevating Abe Silverstein to chief of research.

The reorganization brought a pleasant surprise to the small rocket group. It was moved up one level in the organizational hierarchy, named for what it was, and given more personnel. Silverstein was the highest NACA official to show significant interest in rocket research, although much of it was new to him. One of the things he wanted to understand better was the propellant selection process and, particularly, how candidates for research were chosen.

During the same period, organizational changes were occurring in related military research and development. In 1949, a USAF advisory committee headed by Louis N. Ridenour recommended that the Air Force research and development activities be consolidated into a single command. In January 1950, the Air Force established the Air Research and Development Command which included the facilities at Wright Field and the Air Engineering Development Center at Tullahoma, Tennessee—the latter renamed in honor of General Arnold the following month.

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*The NACA Aircraft Engine Research Laboratory at Cleveland was named the Lewis Flight Propulsion Laboratory in 1948 in honor of NACA's first director of research.

The reassessment of research plans that followed the organizational changes had special significance for the Lewis rocket group in March 1950 when a group of Wright Field officials visited the Lewis laboratory.* The visitors showed considerable interest in rocket research in general and propellant selection in particular. Also discussed were the merits of forming a NACA subcommittee on rockets, a need recognized by the Durand committee nearly a decade earlier.

Conference on Propellant Selection

Apparently as a direct result of the visit by Wright Field officials, the NACA called a meeting of rocket experts at the Lewis laboratory on 19 May 1950 to discuss the selection of rocket propellants for long-range missiles.[12] A secondary purpose was to use the meeting as a "test run" to determine if a NACA subcommittee on rockets was desirable and feasible.

Propellant selection for any mission is always a compromise between performance and other desired characteristics such as density, cooling capacity, storability, handling, and availability (appendix A-4). The selection process had advanced through several levels of sophistication. The simplest method used exhaust velocity as the criterion, since range varies approximately with the square of exhaust velocity. This ignores the effect of propellant density, which affects tank and vehicle size and mass. In 1947, Richard Canright of the Jet Propulsion Laboratory developed a method of relating exhaust velocity and propellant density for large rockets and found that exhaust velocity was the more important of the two. Combinations using liquid hydrogen ranked the highest, although Canright favored hydrazine for its overall characteristics (p. 47–48). Later studies involved more complex considerations of missile design and flight than Canright's, but all suffered from lack of data that could be obtained only when rockets were designed, built, and flown.

In addition to the major flight parameters, the military was very interested in the logistics problems of propellants—such characteristics as vapor pressure, freezing point, stability during storage, corrosiveness, toxicity, availability, and cost.

At the Lewis meeting, the military representatives and their contractors presented their views and research results. The NACA-Lewis recommendation for propellants, presented by the author, consisted of a primary selection and alternatives. The primary fuel was liquid hydrogen and the primary oxidizer was liquid fluorine. If propellant density proved too great an obstacle for liquid hydrogen in a practical application, the alternate fuels selected were hydrazine, ammonia, or a mixture of the two. The Lewis choice of alternative oxidizer was oxygen.

The NACA recommendation, its first firm choice of liquid hydrogen as a rocket fuel, was not opposed by anyone at the meeting. After all, the selection was for research

*They were: Col. Marvin Demler, chief of the power plant laboratory; Lt. Col. J. M. Silk; Opie Chenoweth, chief scientist; C. W. Schnare, in charge of rockets; E. C. Simpson, in charge of turbojet engines; W. A. Wolfe; E. Brown; and R. E. Ray. NACA attendees were: Edward R. Sharp, Abe Silverstein, E. J. Manganiello, Walter T. Olson, Willson Hunter, John H. Collins, Jr., and the author.

purposes, not for a development. The selection of alternatives reflected the uncertainty over the effect of fuel density on long-range missile design and performance. The NACA position satisfied both those who believed in the potential of liquid hydrogen and those who did not.

Views about using liquid fluorine, however, varied considerably. During the morning session, William Doyle, of Ohio State University, listened with growing impatience to presentations by Rocketdyne and Aerojet on their fluorine experiments. As a strong advocate of both liquid hydrogen and liquid fluorine, he felt that the presentations were too pessimistic. He could hardly wait to rebut them, but lunch intervened. After lunch, the meeting chairman, Abe Silverstein, noted the meeting was behind schedule and cancelled discussion of the morning papers. This was too much for the peppery Doyle who jumped to his feet, announced that he knew more about fluorine than anyone else present, and proceeded "to lambast the hell out of the two fluorine papers" for their pessimism. Silverstein allowed Doyle to make his point before clamping down.[13]

Following the May propellant selection meeting, the NACA rocket group planned experiments with liquid hydrogen but faced the familiar problem: how to get a supply of it. Obtaining dewars of liquid hydrogen from Herrick Johnston at Ohio State University and transporting them to Cleveland was rejected as impractical. Since it was not available commercially, the only course open was to build a liquefier at the laboratory. Since the money needed was too much to come from operating funds, the NACA, for the first time, went to Congress in 1951 with a request specifically for rocket research. The fiscal year 1952 budget for construction of facilities contained an item of $150000 to buy a hydrogen liquefier and a building to house it. The justification stated in part:

> Of the chemical combinations that are available as propellants for rocket engines for maximum range, liquid hydrogen offers great potentialities. With certain oxidizers liquid hydrogen has the greatest thrust-per-pound propellant flow [exhaust velocity] of any of the chemical combinations, an important factor for long flight. Insufficient experimental research has been done in this Nation on the use of liquid hydrogen with suitable oxides [sic]. . . . Although there are no commercial cuppliers of liquid hydrogen, simple liquefaction equipment developed during the war, is available commercially.[14]

Congress approved the request and NACA contracted with the Arthur D. Little Company of Cambridge, Massachusetts, for a hydrogen liquefier scaled up from a Collins cryostat. The company ran into some difficulties which delayed delivery, and the NACA spent the interim period investigating other high-energy rocket propellants.

NACA Rocket Subcommittee

NACA officials were pleased with the outcome of the May 1950 meeting of rocket experts and the following January established the Special Subcommittee on Rocket Engines under the Power Plants Committee. The chairman was Professor Maurice J.

Zucrow of Purdue University, a well known and respected authority on jet propulsion.*

Establishment of the rocket subcommittee represented a significant milestone in NACA recognition of the importance of rocket research. In addition to its great value for coordinating and exchanging information on rocket research and development, the subcommittee was a political force for assuring a fair share of attention to rocket propulsion. Although the number of research personnel assigned to rocket research at the NACA Lewis laboratory was still small—less than 3 percent—the group had the strong support of both Silverstein, an associate director of the laboratory, and a body of national experts on rockets whose advice and recommendations would carry weight.

Research Conference on Supersonic Missiles

On 13 March 1952, the NACA held a research conference at the Lewis laboratory to present the latest results of research pertaining to supersonic missile propulsion. Papers on turbojet and ramjet propulsion dominated the meeting, but there was one paper on the status of liquid-propellant rocket engines by Gerald Morrell and Vearl Huff. Their paper covered propellants, combustion, and cooling—the three subjects of NACA research. Experimental performance data for rocket engines using ammonia and ammonia-hydrazine mixtures as fuels and liquid fluorine as the oxidizer were presented. With respect to high-energy propellants in general, the authors stated:

> The high specific impulse [exhaust velocity] propellant systems are of greatest promise for application in long-range missile propulsion; recommendations for propellant systems which require development include hydrogen-oxygen, hydrogen-fluorine, and ammonia-fluorine. Experience with these systems is still in the early experimental stages, but the performance obtained to date is encouraging. With the hydrogen-oxygen system, other laboratories (JPL, Aerojet and Ohio State) have obtained 96 to 97 percent of the theoretical specific impulse calculated for equilibrium expansion; that is, maintenance of chemical equilibrium is assumed during the expansion process. Experiments with the hydrogen-fluorine system in a 100-pound-thrust [445 newton] engine at JPL have yielded equally good performance.[15]

Boost from the Subcommittee

Since the start of the Korean conflict in 1950, the NACA had submitted larger budget requests for aeronautical research each year, only to have the requests cut

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*Other members: Richard B. Canright, JPL-CIT; Comdr. K. C. Childers, USN, Bureau of Aeronautics; R. Bruce Foster, Bell Aircraft; Stanley L. Gendler, Rand Corp.; Joseph L. Gray, Office of Chief of Army Ordnance; Paul R. Hill, NACA-Langley; G. E. Moore, General Electric; Thomas E. Meyers, North American Aviation; C. W. Schnare, Wright Air Development Center; Jack H. Sheets, Curtiss-Wright; Capt. Levering Smith, USN, Naval Ordnance Test Station; R. J. Thompson, Jr., M. W. Kellog; Paul Winternitz, Reaction Motors; David A. Young, Aerojet; the author; and Henry E. Alquist, NACA, secretary. The next year, Lt. Col. Langdon Ayers, USAF, replaced Schnare; Eugene Miller of Redstone Arsenal replaced Gray; and Benson E. Gammon, NACA, replaced Alquist.

sharply in final appropriations by an economy-minded Congress. Within the NACA, the rocket subcommittee, aided and abetted by the NACA rocket group, became convinced the NACA was not doing enough rocket research. To support this view, a comprehensive review of the NACA rocket program was conducted at the 26–27 June 1952 meeting of the subcommittee. By this time, theoretical work on propellant performance, carried out with the aid of computers, was far ranging and included hydrogen with oxygen and fluorine. In addition, the relationship of propellants and propulsion systems to missions was being studied. Experimental work centered around ammonia and ammonia-hydrazine mixtures as fuels and fluorine as oxidizer, using small engines. Research with liquid hydrogen was still in preparation.[16]

After reviewing the program, the rocket subcommittee passed a resolution that was to have far-reaching consequences:

> WHEREAS, The rocket propulsion research effort of the NACA is highly commendable and of good quality, and
>
> WHEREAS, The NACA rocket propulsion research activity is at much too low a level to be consistent with the importance of rocket propulsion to military services, and
>
> WHEREAS, The rocket propulsion research at the NACA is, in general, being conducted on equipment which is of such small scale that the results obtained are only of limited value to the rocket engine contractors, and
>
> WHEREAS, A function of the NACA is to serve the rocket propulsion industry as an advanced research agency,
>
> BE IT RESOLVED, That the Special Subcommittee on Rocket Engines recommends to the NACA that the research activity on rocket propulsion be expanded and emphasis placed on a broader and more advanced approach to the solution of rocket propulsion problems.[17]

The subcommittee then listed nine problem areas that should be added to the NACA program, but none mentioned hydrogen or other high-energy propellants.*

The rocket subcommittee resolution was presented to the parent Power Plant Committee by Zucrow; it was approved and passed to the NACA Executive Committee, which also approved it. Word passed from Washington to Cleveland to intensify the planning of rocket facilities.

Plans for Rocket Facilities

By 1952, the Lewis rocket facilities consisted of four original test cells and four newer and larger cells built with operating funds by the "Hurry-Up Construction

*They included scaling factors for designing large-thrust rockets, causes and remedies of combustion oscillations, composite and multiple-stage missiles (in cooperation with structural and aerodynamics research teams), nitrogen oxides as oxidizers, rocket propulsion for fighter aircraft, problems of using nitric acid as an oxidizer, variable-expansion nozzles, and altitude performance of rockets.

Company"—the self-styled, in-house construction group. With the word from Washington, the imaginative and ambitious rocket group began turning out a series of grand plans for rocket testing that required a huge site in a remote area of the West. These went far beyond the intent of NACA officials and the bubbles burst one by one, until planning narrowed down to what could be built at the Cleveland laboratory site. By the time the NACA executive committee approved the rocket subcommittee's resolution, NACA had decided to request an $8.5 million rocket-engine facility at the Lewis laboratory. It was described at the November 1952 meeting of the rocket subcommittee by Walter T. Olson and the author.[18]

The proposed facility provided complete engine systems research using two major classes of propellants: high-energy propellants for long-range missiles, and high-availability, low-cost propellants for boosters, superperformance aircraft, and medium-range missiles.* The facility was unique in four features: (1) high thrust and long durations (89 kN and 3 min. for high-energy propellants; up to 445 kN and 3 min. for high-availability propellants); (2) hydrogen liquefaction and fluorine generation and liquefaction in quantity at the test site; (3) exhaust-gas scrubbers, designed from data provided by NACA research, to remove hydrogen fluoride from the exhaust; and (4) silencing equipment to muffle the rocket's roar.

The subcommittee endorsed the proposed facility and its chairman, Maurice Zucrow, added his hearty endorsement.[19] This support was crucial but despite it, the attrition process that had befallen earlier plans reappeared at the Bureau of the Budget. The rocket group began to get telephone calls about cutting various features to reduce the cost. One of the first items to go was the fluorine plant, but this was not too serious as Allied Chemical was becoming interested in supplying fluorine for rocket applications.† Hans Neumark of Allied Chemical, under contract with the Air Force, was developing an over-the-highway trailer for transporting liquid fluorine. The next item to go from the proposed facility was the hydrogen liquefaction plant, followed by the large-scale facilities for engines of 445 kilonewtons. The rocket group became depressed as they watched their dreams melting away. One day a call came from Washington: What can you do for $2.5 million? The answer: the high-energy propellant features with exhaust-gas scrubber and silencer. This was accepted and the facility was authorized and funded by Congress. Construction began in 1953 with scheduled completion in 1956. During this period, an existing rocket test-cell was modified to handle high-energy propellants in engines of 22 kilonewtons and the Arthur D. Little hydrogen liquefier was installed. The research program remained essentially the same, but four years after selecting liquid hydrogen as its first choice, the NACA had yet to experiment with it.

In spite of the increased NACA support, rocket research remained comparatively small during the construction of the new facility. Disappointed, the rocket subcommittee at its October 1954 meeting noted that the NACA was spending twice as

*The high-energy propellants were liquid hydrogen, hydrazine, and ammonia as fuels, with fluorine and oxygen as oxidizers. The high-availability propellants were hydrocarbons as fuels with nitric acid and liquid oxygen as oxidizers.

†Six years later (October 1958), the author participated in opening ceremonies of Allied Chemical's fluorine plant at Metropolis, Illinois.

much on ramjet research as on rocket research,* whereas the military services were emphasizing rockets, not ramjets—a clear signal that the NACA was about to miss the boat again as it had earlier with its late start in jet propulsion.

Switch from Air-Breathing to Rocket Engines

Up to 1952, military concepts for long-range missiles emphasized rocket-boosted, winged missiles powered by air-breathing engines.† Beginning that year, a series of events brought great changes in military thinking about strategic missiles. These events, according to Herbert York, a participant, were "the invention and demonstration of the hydrogen bomb, the election of Eisenhower and the concomitant extensive personnel changes throughout the executive branch, . . . and the growing accumulation of intelligence reports . . . that the Soviet Union had already launched a major program for the development of long-range rockets."[20]

In June 1952, the Department of Defense established a study group on guided missiles which led to the Strategic Missiles Evaluation Committee, chaired by John von Neumman, the famed mathematician.‡ The von Neumman committee studied the Air Force's strategic missile program and reported in February 1954 that both the missile systems and their specifications were out of date and unsatisfactory. An urgent need for greater strategic missile capability was seen because of improved Soviet defenses against manned bombers as well as rapid development of Soviet strategic missiles. The committee pointed out that progress in weaponry research allowed reduction of warhead mass as well as a relaxation of accuracy requirements.[21] The von Neumman committee recommendations had great influence and when adopted and implemented, long-range missile development swung from winged missiles using air-breathing engines to ballistic rockets—the beginning of the accelerated ballistic missile development of the 1950s. In the first series of liquid-propellant missiles, the propellants were a kerosene-like hydrocarbon and liquid oxygen.

The choice of a single propellant combination for development of long and intermediate range liquid-propellant ballistic missiles did not stop research on high-energy propellants, which became candidates for a second generation of improved missiles.

The NACA was not oblivious to the changes in military emphasis from air-breathing to rocket engines, but took no strong steps to realign its research emphasis until about 1956. Meanwhile, the small rocket group at the Lewis laboratory was steady on its course and late in 1954 was ready, at long last, to experiment with liquid hydrogen.

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*In October 1954, NACA rocket research was $1.2 million or 2.4 percent of the budget; ramjet research was $2.5 million or 5.1 percent of the budget. Minutes of meeting, NASA History Office.

†Three strategic missiles in development were: Snark, a winged cruise missile, developed by Northrop and powered by a turbojet engine after assisted take-off with solid-propellant rockets; the Matador, developed by Glenn L. Martin, similar to but smaller than the Snark; and the largest, Navaho, developed by North American Aviation, powered by a ramjet engine after boost to supersonic speeds by three liquid-propellant rocket engines.

‡Other members: George Kistiakowsky, Charles A. Lindbergh, Simon Ramo, Jerome Wiesner, and Dean Wooldridge.

First Attempt to Use Liquid Hydrogen

When the rocket subcommittee met in October 1954, preparations for the first experiment with liquid hydrogen were almost complete. The liquefier was producing liquid hydrogen. One of the larger test cells had been equipped to use liquid hydrogen with either of two oxidizers—liquid oxygen or liquid fluorine. Edward Rothenberg headed the team using hydrogen-oxygen and was ready first.* On 23 November 1954, the first successful run with liquid hydrogen was made; thrust and chamber pressure were at design values and exhaust velocity was 90 percent of theoretical. Ten days later, two more successful runs were made, but performance data were incomplete. A fourth successful run on 6 January 1955 yielded lower performance than the previous runs.[22]

After the four successful runs with liquid hydrogen-oxygen in 22-kilonewton engines, no more experiments with liquid hydrogen were undertaken for almost a year. The reasons were several. One was a need to reassess injector design. On the first three runs the oxidizer injection rings had burned, and the low performance of the fourth was a clear signal of poor injection. Another reason was a need for improved start and shutdown techniques. Although a satisfactory method had been worked out, it depended a good deal on the reaction time and skill of the operator. In starting, a low hydrogen flow was ignited outside the engine and flashed back into the engine when oxygen flow began. When flashback occurred, full hydrogen and oxygen flows were established. After the first run, the operators discovered that a fire had started during the ignition phase, which ignited hydrogen escaping from the supply tank. The problem was solved by opening the hydrogen valve and burning the escaping hydrogen until the tank was exhausted. The experience was somewhat similar to the leaks encountered by Walter Thiel in Germany about 1937 (p. 269).

Two other factors contributed to the delay in hydrogen testing. The Air Force loaned the laboratory the mobile hydrogen liquefaction equipment developed by Herrick L. Johnston (fig. 14) which would produce almost twice as much liquid hydrogen as the installed equipment and help keep pace with growing demands for hydrogen in other laboratory work. Glenn Hennings of the rocket staff was placed in charge of getting the mobile equipment into operation. The other factor was increasing interest in the possibility of upgrading the performance of existing missiles using JP fuel–oxygen by adding a small quantity of fluorine to the oxygen.† The fluorine not only increased performance but made the combination self-igniting. By 1955, three reports had been written on investigations of JP-4 fuel with mixtures of oxygen and fluorine.[23] This concept was not tried in a missile, however, because of concern over the toxicity of fluorine.

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*Paul Ordin headed the team working with hydrogen-fluorine in 1954 and planned performance and regenerative cooling experiments. However, Silverstein picked Ordin to head a special hydrogen flight project (described later), and Howard Douglass took his place. For various reasons, the hydrogen-fluorine experiments were delayed until 1957.

†JP (jet propulsion) fuel was the designation for the petroleum blend similar to kerosene, used at the time. Later rockets used RP (rocket propulsion) fuel.

The rocket subcommittee was still concerned over the low level of NACA rocket research when it met in November 1955.* A resolution was passed detailing the importance of rocket research, the concern over the low level of NACA activity, and the problems needing attention; it ended by recommending the NACA effort "be considerably increased so that significant progress can be made at the pace keyed to the swiftly moving national defense effort in rocket propulsion."[24] Development of the Atlas and Titan ICBMs and Thor and Jupiter IRBMs was accelerating and subcommittee members from propulsion and airframe manufacturers as well as the military were feeling the pressure. They believed that the NACA ought to help solve their development problems.

NACA officials recognized the increased emphasis on missiles but continued research on advanced air-breathing engines as well. In the 1955 NACA annual report, Chairman Hunsaker stated: "Today, problems associated with a nuclear engine for aircraft propulsion and with an intercontinental ballistic missile are perhaps the most pressing."[25] The nuclear engine for aircraft was soon to fade into oblivion, but the intercontinental as well as the intermediate-range ballistic missiles became key elements in U.S. military preparedness.

Second Attempt to Use Liquid Hydrogen

In December 1955, the Lewis rocket team resumed experiments with liquid hydrogen but with slight success. Seven runs were made on the 8th and 10th of December; two engines burned out. A successful run was made on 16 February 1956, followed by three more two weeks later. Preparations were then made to operate with liquid hydrogen–fluorine. On 9 March, the first attempt was made, but the engine burned out in four seconds. This was long enough, however, to measure performance: thrust and pressure were near design values and exhaust velocity was 3510 meters per second, or 93 percent of theoretical.[26] This was the highest rocket performance value obtained at the Lewis laboratory up to that time. Cooling, however, remained an obvious problem, and emphasis was placed on it.

NACA Reconsiders Missiles

Although the NACA had always maintained an interest in the problems of high-speed flight and had made some significant contributions,† actual effort remained relatively small until about 1956. Meanwhile, the military ballistic missile effort had risen rapidly since early 1955; in FY 1956, it passed the half-billion-dollar mark and was nearly three times larger the next year.[27] Interest in extending ballistic missile

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*Thomas E. Myers of North American Aviation replaced Maurice Zucrow as chairman in 1954, with Zucrow continuing as a member. Other members: Lt. Col. Langdon F. Ayers, USAF-ARDC; R. B. Canright, Douglas Aircraft; B. F. Coffman, Bu. Aer., Navy; H. F. Dunholter, General Dynamics; R. B. Foster, Bell Aircraft; W. P. Munger, Reaction Motors; J. R. Patton, Office of Naval Research; C. C. Ross, Aerojet-General; C. N. Satterfield, M.I.T.; F. E. Schultz, General Electric; A. J. Stosick, JPL; R. C. Swann, Redstone Arsenal; F. I. Tanczos, Bu. Aer., Navy; the author, NACA-Lewis and B. E. Gammon, secretary.

†For example: the blunt-body theory for warhead reentry into the atmosphere from a ballistic trajectory conceived by Harvey Allen of NACA-Ames in 1951 and published in the open literature in 1958.

capabilities to launching satellites was also growing. In NACA's 1956 annual report, Chairman Hunsaker recognized the need for more missile research and added, "we are striving for the knowledge that will make possible satellites probing the regions beyond the earth's atmosphere . . . ."[28]

Following up on the need for greater effort in both aircraft and missile research, the NACA established a panel to determine the type of facilities required for the coming years. Hugh L. Dryden, NACA's director of research, wrote to Thomas Myers, the rocket subcommittee chairman, acknowledging the three-year attempt by the subcommittee to increase rocket research and informed him that the facilities panel "now has under consideration . . . a proposal for a rocket systems research facility to provide the necessary space and equipment to implement the Subcommittee's recommendation."[29] Dryden was fully aware of the new high-energy propellant facility nearing completion at Lewis and had in mind "basic research leading to improved turbopump designs for rocket engines and to improvements in propellant systems generally." Dryden had pinpointed a deficiency in NACA research that could be swiftly remedied. Since its formation in 1945, the Lewis rocket group had been limited to problems associated with the thrust chamber of a rocket engine system. The laboratory had a large division specializing in compressor and turbine research for jet engines; a technical field closely related to turbopumps of rocket engines. By building suitable facilities for turbopumps and complete engine systems, NACA could tap this pool of technical talent and accelerate its contributions to missile problems.

In his letter to Myers, Dryden asked for comments and answers to specific questions such as, "Why should NACA enter the field of rocket propellant systems?" His choice of words was unfortunate for apparently Myers thought he meant rocket propellant combinations. Myers replied with an eloquent plea for NACA research on propellants, giving three reasons: high-energy propellants can increase missile range by an order of magnitude or for satellites, permit increases in payload; improved propellant systems have multiple applications and research data from NACA spread throughout the country have a beneficial effect on rocket developments; and the NACA's achievements in propellant research are widely recognized and used by the rocket industry.[30]

Advanced Propulsion Concepts

Dryden's request to Myers was typical of NACA's conservative approach in entering a new field—solicit opinions and build a broad base of national support so that it would appear the agency was practically pushed into the new work. This process continued when Myers, at the May 1956 meeting of the rocket subcommittee, asked the members for suggestions for rocket research for the next 10 to 15 years. By the fall of 1956, the responses were grouped into five discussion topics, one of which was high-energy propellants, but without specific reference to liquid hydrogen.* In discussions of these topics in meetings the following year, evaluation of high-energy propellants

*The others: nonconventional rocket propulsion, such as solar energy, ions, electrons, charged particles, and free radicals; nuclear energy; comparison of nuclear and non-nuclear propulsion; and summary of the other topics from the viewpoint of applications and military requirements.

was of first-order importance, but again no specific propellant combinations were singled out.[31] The NACA-Lewis rocket group, however, was still greatly interested in liquid hydrogen and believed that they had the support of the rocket subcommittee.

In mid-1957, at the invitation of the chairman of the NACA subcommittee on aircraft fuels, Richard Canright (who had left JPL for Douglas Aircraft in 1953) submitted a paper on rocket propellants as viewed by an airframe manufacturer. Canright had a long interest in rocket propellants and his employer, Douglas Aircraft, had development contracts involving both solid and liquid rocket engines. From this viewpoint, he dismissed the application of air-breathing engines for missiles as "extremely limited if not completely non-existent." After discussing the relative advantages of solid and liquid rocket propellants, Canright gave his views on liquid hydrogen:

> This is, of course, the non-carbonaceous fuel that offers the highest performance of any fuel. However, because of its low density, it is useful only in certain extreme applications. Hydrogen offers excellent combustion characteristics, both in the gas generator and in the main motors, and good heat transfer characteristics in the supercritical regime; on the other hand, it is hazardous to handle and there is no large engine experience with this fuel to date.[32]

Except for the mention of combustion and heat transfer characteristics, Canright offered little more on liquid hydrogen than Tsiolkovskiy 30 years earlier, an indication of the continuing gap between what was known about liquid hydrogen and its practical application.

When asked to summarize the contributions of the rocket subcommittee in its five years of existence, Canright replied:

> We have constantly spurred the NACA on to tests on a larger scale. We have urged them to become familiar with complete engines rather than work only on component R&D. We have tried to emphasize the importance of rocket technology to this country's defense effort and urged that the NACA devote a greater portion of its personnel and funding to this important field.[33]

He added, however, that NACA interest in high-energy propellants was praiseworthy and that the subcommittee supported it.

High-Energy Propellant Facility

The new $2.5 million rocket facility for high-energy propellants, requested in 1952, was completed in the fall of 1957 (fig. 15). It comprised a test cell, propellant supply system, and a unique combination exhaust-gas treatment and silencing system. A service building and high-pressure helium bottles were adjacent to the test cell. Farther away were storage areas for fuels (hydrocarbons, ammonia, hydrazine), liquid oxygen, and water for the scrubber, all piped to the test cell under gravity. Fluorine was loaded into propellant pressure tanks from trailers and a similar provision was made for liquid hydrogen. The oxidizer tanks were in a pit behind the cell, suspended on a weighing system within another tank into which liquid nitrogen was placed as a coolant when

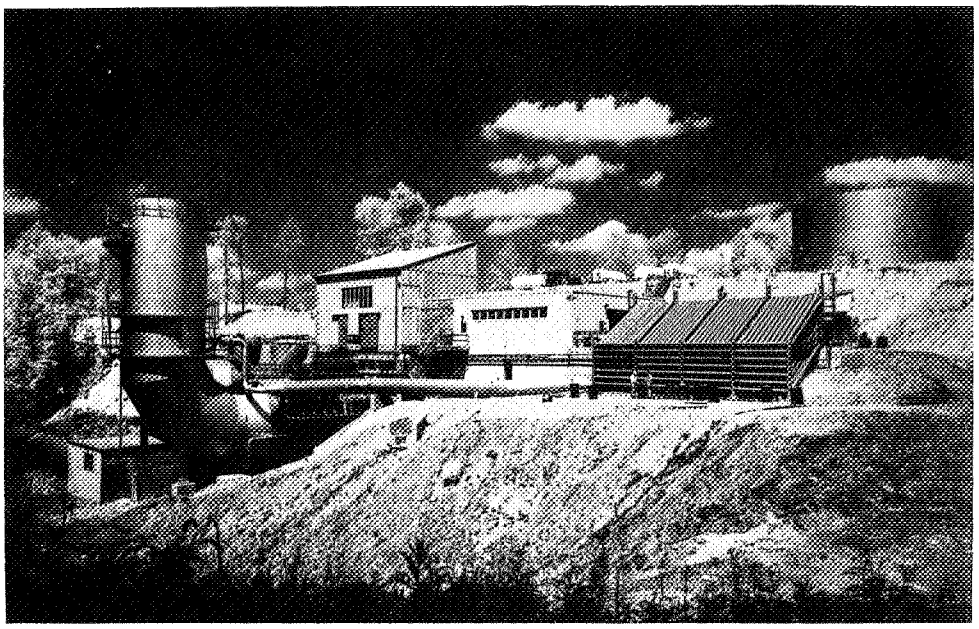

Fig. 15. The NACA-Lewis high-energy rocket propellant test facility, placed into operation in 1957. The building with the slanted roof is the test cell. The large horizontal duct with vertical stack is the exhaust-gas scrubber and silencer. The two men are in front of racks of high-pressure cylinders of helium used for pressurization. On the far right is the water storage tank and on the far left is the water detention tank and treatment system.

fluorine was used (fig. 16). The tanks and system were sized to allow three minutes of operation at a thrust of 89 kilonewtons, a considerable increase in size over other high-energy rocket facilities in the country. The exhaust duct at the rocket nozzle exit was 3.7 meters in diameter; the horizontal section, 7.6 meters, and the vertical stack, 6 meters. During a run, water from the 1500-cubic-meter (400 000-gallon) tank on the upper level flowed to the exhaust scrubber at a rate of 190 cubic meters (50 000 gallons) per minute. This was well over a hundred times the mass flow of exhaust gases. The hot gases, emerging from the nozzle at velocities of 3000–4000 meters per second and temperatures of about 2300 K, were met with a drenching spray of water and quickly cooled to steam temperature and slowed to a velocity of about 8 meters per second. Additional water sprays condensed the steam, and the non-condensable exhaust gas emerged from the stack at about 340 K and a velocity of 3 meters per second. The hydrogen fluoride of a fluorine-hydrogen rocket is highly soluble in water; the water containing it was collected in the detention tank. After the run, calcium hydroxide was introduced into the detention tank and the hydrogen fluoride converted to calcium fluoride—which is inert and harmless—and a slurry of it was pumped into tank trucks and hauled to a dump. The facility was equipped with barrels containing ordinary charcoal and connected to the fluorine system. Harold Schmidt of the rocket research group had found that fluorine reacts readily with charcoal and is converted into inert carbon fluorides—an excellent way to dispose of unwanted fluorine. Monitors to sniff

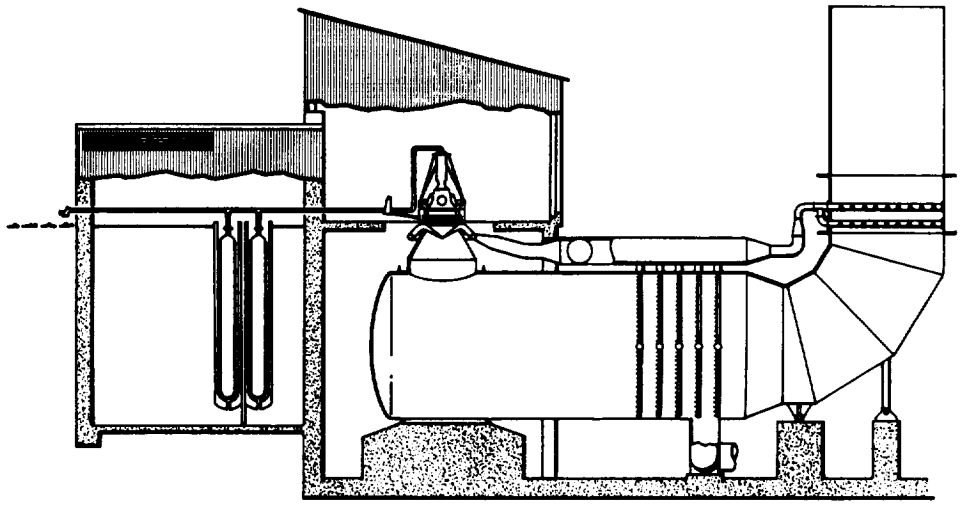

Fig. 16. Sectional view of the NACA-Lewis rocket facility. On the left are high-pressure propellant tanks in pits. The rocket engine and test stand, for vertical downward firing, are dwarfed by the large ducting for exhaust gas scrubbing and silencing.

a variety of gases and combustible mixtures were located at strategic places about the test area. The test cell was controlled by a well-equipped center in the rocket operations building about a kilometer away.

Thrust Chamber Design and Fabrication

The initial failure of the Lewis experiments with liquid hydrogen was primarily one of thrust chamber design. The key to a successful design lies in the injector which can mean high or low performance, durable operation or quick burnout. The function of the injector is to mix the fuel and oxidizer thoroughly and uniformly for complete combustion, while the propellants also cool the injector face. With a good injector, combustion chamber design becomes a matter of providing sufficient volume for the reaction to go to completion, sufficient wall strength to contain the pressure, and sufficient cooling to keep wall temperature within its working limits. The design of the nozzle involves a compromise between providing the optimum contour for complete gas expansion and size, the latter limited by vehicle design.

Rocket experimenters exploring the performance of various propellant combinations usually used either a water-cooled thrust chamber and nozzle or uncooled types that could withstand high temperatures for a few seconds. Most effort was concentrated on obtaining an injector yielding high performance. Following this, the next step was to cool the chamber and nozzle with the fuel. We have already seen that both the Jet Propulsion Laboratory and Ohio State University succeeded in operating regeneratively-cooled hydrogen-oxygen thrust chambers during the 1940s. The Lewis experimenters were trying the same but with larger engines (22 and 89 kN), combining regenerative cooling with thrust chambers of light weight to approach a practical flight design. These objectives had been spelled out in 1952 and reaffirmed each year.

The first injector used for liquid hydrogen–liquid oxygen at Lewis in 1954 was a like-on-like impingement where jets of the same fluid impinge, breaking the streams into droplets. Mixing is obtained by locating the impinging streams of fuel and oxidizer near each other so that the resulting droplets mix well. Ohio State University used this type and it was popular among rocket experimenters. JPL used an injector with impinging hydrogen jets and an oxygen spray. Aerojet's best injector was a multiple-tube, concentric type where each jet of hydrogen was surrounded by a sheath of oxygen (fig. 10). The three successful runs by the Lewis group in February 1956 used a "tube bundle" injector where a large number of small tubes carried the hydrogen and oxygen into the chamber with a fine degree of mixing.

By all experience and design principles, the hydrogen-fluorine injector used in the first Lewis laboratory run in March 1956 should have worked well. It consisted of four rings of hydrogen holes producing streams parallel to the combustion chamber axis, alternating with four rings of similar holes for fluorine. The holes were small and mixing was good; but when tried, the operator summed the results in four cryptic sentences in his log:

> H_2-F_2 was run on "B" stand, Cell 22. Made only 1 run. Injector burned out causing chamber to go. Run time=4 sec.[34]

Parallel to these experiments, more detail studies were under way at the Lewis laboratory on fundamentals of injector design. Such work had been in progress since the early 1950s, but it was not until 1956 that experiments in this basic work focused on hydrogen. Carmen M. Auble studied six types of injection methods for hydrogen-oxygen in a small (900 N) thrust chamber.[35] Gaseous hydrogen, chilled to the temperature of liquid nitrogen (77 K), simulated the physical characteristics of hydrogen after it served as a coolant prior to injection. Not surprisingly, Auble found correlation between the mixing and spreading of the propellants and performance over a range of propellant mixture ratios, all his designs doing well at fuel-rich ratios. Increasing the temperature of the hydrogen to room temperature was beneficial. Compared with hydrocarbon fuels, hydrogen needed a fifth as much volume for comparable combustion efficiency. Separate and parallel jets, as used in the hydrogen-fluorine run, did as well as injectors that promoted mixing. Auble found, however, that combustion efficiency was controlled more by the degree of oxygen vaporization than by hydrogen dispersion and mixing.

Late in 1957, Marcus F. Heidmann and Louis Baker, Jr., extended Auble's investigation, combining it with earlier analyses of propellant vaporization as a rate-controlling step in combustion. They investigated fourteen injectors for hydrogen-oxygen in an engine of the size that Auble had used. Their investigation confirmed that the degree of oxygen atomization was the primary factor affecting combustion efficiency.[36]

Concurrent with injector and performance studies were several investigations of fabrication techniques for lightweight and cooled combustion chambers and nozzles. In 1953, John E. Dalgleish, a fabrication expert, and A. O. Tischler, a rocket researcher, worked together on lightweight thrust chambers using an electroforming technique.[37] In 1954, Tischler placed orders in the shop for two other types. One used tubes formed according to the contour of the combustion chamber and nozzle and

brazed together—a method used by several rocket manufacturers starting with Reaction Motors. The other type was similar except that, instead of tubes, channels were formed and then brazed or welded together with a closure over the channels to complete the coolant passage and strengthen the whole assembly. Both of these experimental types were still in the shop two years later as they had been given a low priority.

Until 1956, the primary responsibility for designing thrust chambers rested with an engineering service group headed by William A. Anderson. He developed a fabrication technique consisting of an inner shell of spun metal, wire spacers to form spiral coolant passages on the outside of the shell, and a welded "clam-shell" outer wall to enclose the coolant passages. A variation of this method was to form the outer shell of square wire brazed together. The Anderson design was successfully used on engines of 4.5 kilonewtons and was the prime design for larger engines until 1956–1957.

Obtaining experimental engines was hampered by increasing congestion in the fabrication shop. The NACA shops were unexcelled in advanced fabrication techniques and willingly accepted all challenging work, but delivery was sometimes delayed by an avalanche of orders or work of higher priority. In 1956, the shops had orders for over a dozen thrust chambers of various designs and delivery was delaying experimentation. Steps were taken to reduce the number of designs, and Silverstein assigned Edward Baehr, a gifted design and fabrication engineer, to assist the rocket group. Baehr made a major contribution to the rocket effort by choosing a design something like Tischler's channel-wire wound type and successfully fabricating it. It consisted of a number of longitudinal channels of varying depth according to the coolant velocity required. These were bonded together to make up the chamber and bound by stainless steel wire wrapping which was brazed to make a fluid-tight and strong outer skin (fig. 17). This design was used in 1957 and subsequently.[38]

Since the early 1950s, Lewis associate director Abe Silverstein had been interested in liquid hydrogen as a fuel for both jet engines and rockets. In the spring of 1957, he decided that it was time to hold a research conference on results of the laboratory's investigations. That conference, plus additional emphasis on rocket research at the laboratory, meant unprecedented support for the rocket group, and they made the most of it. Silverstein became more involved in rocket problems and on 9 August 1957 held one of his famous after-hours staff conferences on the subject of injector design. The informal session was held in the control room of the new facility—complete with beer and pretzels, compliments of Silverstein—and ran past midnight. Everyone contributed his views.* The author remembers stressing the concepts of mixing on a very fine scale coupled with uniform mixing except for a fuel-rich cooling region at the chamber walls. These concepts, not new, were adopted along with other design ideas such as selecting angles of jet impingement well away from the injector face, avoidance of recirculation of reactants across the injector face, and fuel-cooling of the injector face. In September, Silverstein held another meeting on injectors as well as other rocket design problems for experiments intended to be reported at the coming conference.[39]

*Attendees were: Silverstein, W. T. Olson, Edward Bachr, Vearl Huff, M. F. Heidmann, A. O. Tischler, Howard Douglass, George Kinney, William Anderson, and the author.

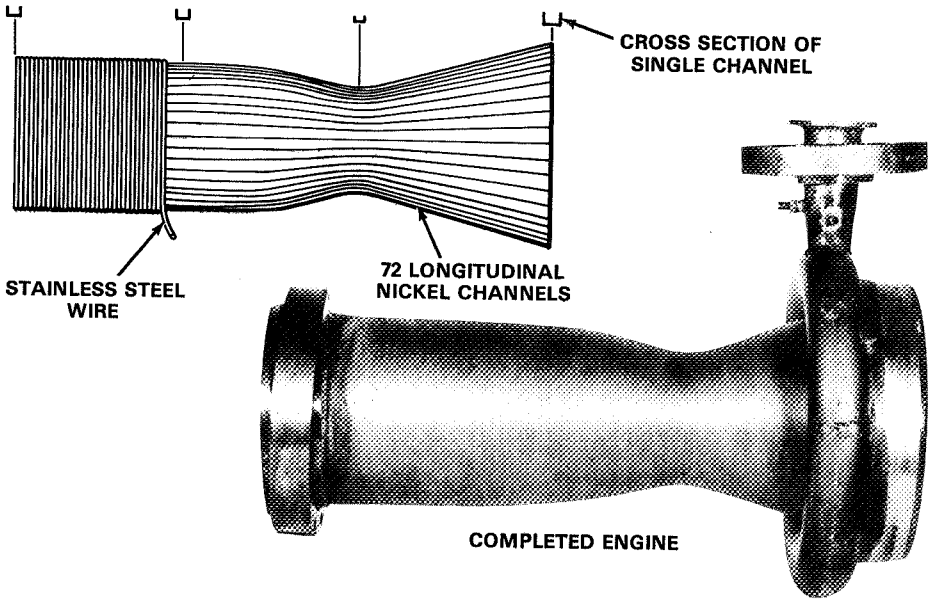

Fig. 17. Experimental rocket chamber of 22 kN, regeneratively cooled. Fabricated by a method developed by Edward Baehr. NACA-Lewis, 1957.

Space Becomes an Acceptable Word

The fall of 1957 was one of fast-paced activity. The new rocket facility at the Lewis laboratory was completed and system checkouts were under way. Plans were made to include it as an exhibit stop in the laboratory's triennial inspection, scheduled for October. These inspections were NACA's way of showing its facilities and latest research progress to congressmen, government officials, professors, engineers from industry, reporters, families, and friends. The affairs were exhaustively planned and rehearsed and executed with split-second precision.

For its part in the inspection, the rocket group showed the great advantages of high-energy propellants, including hydrogen-oxygen and hydrogen-fluorine. As an example, they illustrated the case of a manned satellite in an 1850-kilometer orbit with a winged glider for returning to earth. The use of high-energy propellants would reduce the required booster size and weight by half. The exhibit also demonstrated the powerful oxidizing property of fluorine. A steel bar, chemically cleaned, was exposed to a small jet of gaseous fluorine and nothing happened. The bar was then contaminated by a slightly greasy thumbprint and again exposed to the fluorine jet. The fluorine then reacted with the contamination, the reaction heating the steel bar until it burned—a spectacular and impressive demonstration of fluorine's potency.

Among the many rehearsals was a review by officials from NACA headquarters. The climate in Washington in the fall of 1957 was very negative towards space. It was all right to talk about the slow-paced scientific Vanguard satellite, part of the International Geophysical Year, but anything beyond it was considered "space-cadet"

enthusiasm. When John Victory, NACA executive secretary and one of its original employees, heard the word "space," he ordered that it not be used for fear of offending some of the visitors, particularly congressmen and other government officials. Before the inspection, however, the Soviet Union's Sputnik I put the word "space" in the headlines of every American newspaper, and guests heard the word in many of the laboratory's presentations.

Emphasis on Hydrogen

When the NACA 1957 Flight Propulsion Conference was held at the Lewis laboratory on 21–22 November 1957, it could have been called, as one member of the audience remarked, a conference on liquid hydrogen as a fuel. The primary emphasis was on air-breathing engines, but the rocket group had a sizeable part of the program—the last three of eight presentations.[40] Silverstein had decided that rather than having individual papers, each subject would be handled by a panel taking turns presenting the subject and discussing it. The subjects were broad. The three on rockets were propellants, turbopumps for high-energy propellants, and performance and missions. The last two were firmly on the subject of high-energy propellants, but somehow the one on propellants got out of line. It covered the spectrum of propellants, with high-energy propellants receiving attention only at the beginning and at the end, and even then the emphasis was on cooling rather than performance. This emphasis on cooling was due to circumstances. Of the four panelists on propellants, only Howard Douglass was experienced in investigating high-energy propellants. Two of the panelists were newcomers to rockets; one was studying solid propellants, and the other was a controls specialist. It was characteristic of Silverstein to stimulate research by obligating the staff to a research conference with tight deadlines and by assigning individuals the responsibility of discussing subjects broader than their immediate research. Douglass had intended to cover high-energy propellants more thoroughly and add experimental results, but a series of delays in experimental operations almost caused his discussion to be all theoretical.

First Regeneratively-Cooled Hydrogen-Fluorine Rocket

For many months—since the first run of hydrogen-fluorine in March 1955—Howard Douglass, Harold Price, and Glen Hennings* had worked to design, build, and operate a rocket engine of 22 kilonewtons using liquid hydrogen and liquid fluorine, with the liquid hydrogen serving as a regenerative coolant. Edward Baehr worked with them in designing and fabricating the engine. Two kinds of injectors were designed and fabricated: a showerhead type and an impinging-jet type with two jets of fuel impinging on one of oxidizer (fig. 18). The face of each injector was fuel-cooled.

Hennings was operations chief. A perfectionist ideally suited to cope with the hazards of handling fluorine, he made many equipment changes. Operations with

*Hennings had been in charge of liquefying hydrogen until a liquid hydrogen plant in Painesville, Ohio, built by the Air Force, made liquid hydrogen available to the laboratory in quantity.

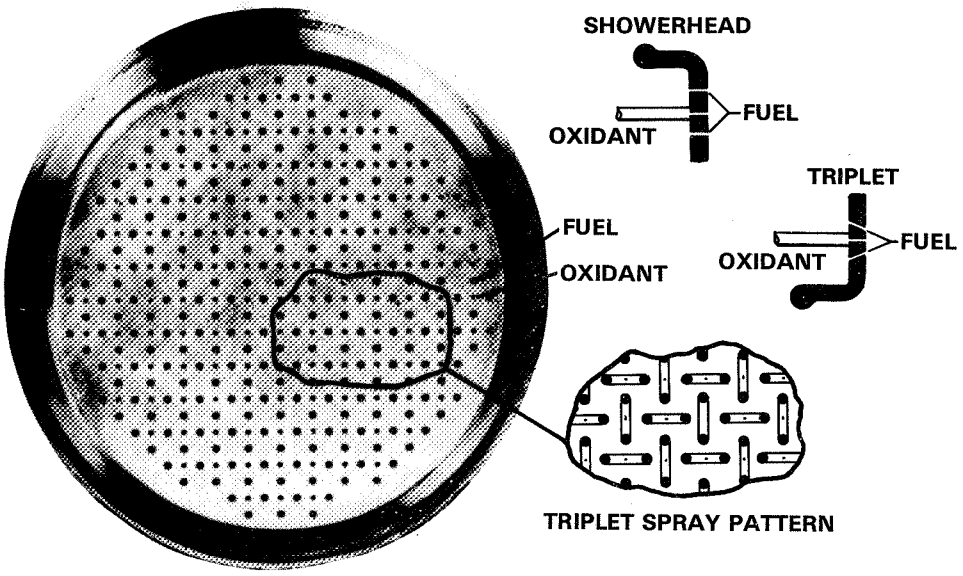

Fig. 18. Showerhead and triplet injectors for rocket engines at 22 kilonewtons using hydrogen-fluorine at NACA-Lewis, 1957–1959. The same general concept was also used for hydrogen-oxygen engines of the same thrust and also for larger engines (89 kN).

fluorine were scheduled for weekends to minimize possible hazards for laboratory personnel working nearby. In a series of attempted runs, an incredible number of problems arose which Hennings doggedly attacked and solved one by one in his careful, methodical fashion. Time was running out, however, and with the conference only a few days away, Douglass drafted his part of the propellants paper around the cooling aspects of hydrogen-fueled engines and hoped for the best.

An attempted run on the weekend before the conference was aborted and prospects appeared grim. Hennings cleared up several vexing problems, determined to operate the engine as soon as possible. On Wednesday evening, 20 November—the day before the conference began—a run was attempted but again problems halted operations. The crew worked all night to solve the problems and through the day Thursday, aiming for another try Thursday night. Douglass was to speak on Friday. The author, fearing that fatigue could cause a misjudgment and an accident, urged the crew to give up, take a rest, and try another day. They continued, however, and worked all through Thursday evening. Finally, at 5:59 Friday morning, they succeeded with a beautiful run that lasted eight seconds, with no sign of overheating. The exhaust velocity measured was 3400 meters per second, 96 percent of theoretical performance. But these values were not known to the tired crew when Douglass went home for a short rest and freshening before his appearance with the panel at 9:30. Harold Price remained to work up the data as fast as possible and bring it to Douglass at the conference.

When the propellants panel began its discussion, Price had not appeared; he was having trouble with security guards because his name was not on the list of those permitted to attend the classified conference. Finally he managed to convince them, hurried to the projection room, marked a data point on Douglass's slide, hurried

downstairs and up the aisle to the stage where he handed Douglass a note with the data and the engine itself, which had been dismounted to display at the conference. He was in the nick of time, for Douglass was the next to speak. Some in the audience thought the entrance was staged, but it was the real thing and a great moment of triumph for the NACA rocket group.[41]

Two other panels at the conference also made a persuasive case for high-energy propellants, particularly liquid hydrogen for rockets. The turbopump panel found no great obstacles in developing turbopumps for hydrogen-oxygen or hydrogen-fluorine combinations and estimated that the mass of such a turbopump would be comparable to one for conventional propellants. The panel on performance and missions found that the greater the energy requirements for a mission, the greater the need for high-energy propellants. For the case of a moon landing and return, the difference in initial mass between vehicles using kerosene-oxygen and those using hydrogen-fluorine or hydrogen-oxygen could be a factor as high as 8 to 1. Silverstein and the Lewis rocket group were convinced that liquid hydrogen was an extremely attractive fuel.

Significance

Although NACA started late in rocket research, kept its effort relatively small, and was but one of many organizations investigating high-energy propellants, its technology contributions were significant to later vehicle developments. NACA was the only government laboratory conducting in-house experiments on high-energy propellants, and NACA data were quickly available to and influenced the work of all other groups. The strong NACA-Lewis preference for liquid hydrogen, which began in 1950 and persisted in spite of delays in securing a supply, was instrumental in keeping others interested in hydrogen. Abe Silverstein, the Lewis associate director, strongly supported liquid hydrogen, and he later occupied a key position in the nation's space program. The NACA rocket subcommittee, a unique body of rocket experts from government, industry, and universities, exchanged information between all interested groups and assisted in national planning of rocket research and development.